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Radiometry Spot Measurement System

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RADIOMETRY SPOT MEASUREMENT SYSTEM

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SUMMARY

The Radiometry Spot Measurement System (RSMS) has been designed for use in the Diffusive And Radiative Transport in Fires (DARTFire) experiment, currently under development at the NASA Lewis Research Center. The RSMS can measure the radiation emitted from a spot of specific size located on the surface of a distant radiation source within a controlled wavelength range. If the spot is located on a blackbody source, its radiation and temperature can be measured directly or indirectly by the RSMS. This report presents computer simulation results used to verify RSMS performance.

INTRODUCTION

The Diffusive And Radiative Transport in Fires (DARTFire) experiment will analyze the steady-state and transient flame data from a burning surface for comparison with theoretical predictions. Transition flame data results from ignition or extinction events. The RSMS is designed to meet or exceed the science requirements established for the DARTFire experiment subject to the physical constraints imposed by the sounding rocket. A pair of plano-convex lenses are selected for the spot measurement function. A bandpass filter is selected for the investigation of the particular spectral region. A high sensitive detector is utilized to measure the small amount of the radiation. This RSMS can measure the emitted radiation specified to within a certain wavelength, and the burning temperature on the black polymethylmethacrylate (PMMA) during the DARTFire experiment. If the PMMA is not black, this RSMS cannot measure the temperature on the burning spot.

SYSTEM DESCRIPTION

The RSMS consists of a thermopile detector, two plano-convex lenses to collect the radiation coming from the desired spot, and a bandpass filter located in front of the lens assembly.

The Dexter-manufactured thermopile detector model 2M with a window of KRS–5 is selected in RSMS. According to the Dexter catalog, its maximum incident radiation accepted is 0.1 w/cm^2 and the incidence range, for a linear signal output, is from 10^{-6} to 10^{-1} w/cm^2. The spectral sensitivity of the detector combined with the KRS–5 window, is 0.60 to 40 μm.

The focal length of one plano-convex lens is 10 cm, the other one is 5 cm (design wavelength is at 11 μm). The lens with long focal length is the objective lens. The objective lens collects the radiation emitted from a small spot on the burning PMMA which is located at its front focal point. The other lens refracts the incidence radiation coming from the objective lens, and focuses it onto the sensing area of the detector. The material of those lenses is KRS–5 which is identical to that of the detector window. The diameters of both plano-convex lenses are 1.27 cm (0.5 in). The lens assembly is the major part of the RSMS.

The wavelength range of the bandpass filter is from 8 to 13.9 μm with ±2 percent tolerance. It satisfies DARTFire science requirement which is from 8 to 14 μm. The transmittance of the filter is 85 percent. All elements are housed in a metal housing as shown in figure 1.

During the measurement, there may be an angle, θ, between the axis of the RSMS and the normal line of the burning surface. The distance between the vertex of the first lens and the center of the spot on the burning sample is 10 cm in the present design. The relative location of the radiometric measurement system is shown in figure 2.

The material used for the detector window and the plano-convex lenses is KRS–5, which has a usable spectral range between 0.6 to 40 μm, with a low water solubility (0.05 g/100 g) and an acceptable transmittance (74 percent). Besides KRS–5, KBr could be selected for its high transmittance, if it has a low water solubility. Currently, KBR–5 is not selected because the water solubility of KBr is too high (53.3 g/100 g).

The whole system is calibrated with the following equipment: a blackbody source model 11–210M manufactured by Graseby IR Systems, and a voltmeter model 3478A manufactured by Hewlett-Packard.

System Design and Analysis

System design.—The DARTFire experiment requires the radiometric system to measure the radiation emitted from a spot on the burning black PMMA. The spot radius should be no longer than 2.5 mm. To meet those requirements, two plano-convex lenses are selected for the main part of the RSMS. The one used to collect the radiation from the burning PMMA is called objective lens, the other used to focus the energy onto the sensing area on the detector is called image lens. Due to the structure configuration, the distance between the burning PMMA and the objective lens should be 10 cm. Similarly, the distance between the detector and the image lens should be 5 cm. With all those constraints, two plano-convex lenses were selected and the specifications are listed in tables I and II.

Based on these data, the lens focal length, the system focal length, the system front focus distance, and the system back focus distance are computed and listed in table III.

The equations (ref. 1) used to compute those parameters are listed below.

$$1/f = (N - 1) * [1/R1 - 1/R2 + t * (N - 1)/(R1 * R2 * N) \tag{1}$$

$$fab = fa * fb/(fa + fb - d) \tag{2}$$

$$B = fab * (fa - d)/fa \tag{3}$$

$$ffd = fab * (fb - d)/fb \tag{4}$$

where

f	is the focal length
N	is the refraction index
R1 and R2	are the curvature radii
t	is the center thickness
fa	is the focal length of the objective lens
fb	is the focal length of the image lens
fab	is the system focal length
d	is the distance between two lenses

B is the system back focus distance

ffd is the system front focus distance

Figure 3 is the image position of the optical system which indicates the relative location of the optical system and the detector with respect to the burning spot. In the figure, h1 and h2 represent the radii of two circles on the burning spot, and the 1-mm length represents the half of the width of the detector sensor area. ffd and B are the computed data in table III.

All the radiation emitted from inside the inner circle of radius h2 can reach the sensor area of the detector. No radiation emitted from outside the outer circle of radius h1 can be detected. Only part of the radiation from the area between the two circles can be sensed by the detector. Table IV lists the computed values of radii h1 and h2. Figure 4 shows the detectable radiation percentage emitted from the spot.

The equations used to compute the radii are

$$h1 = (10.0 - ffd) * 1\ mm/ffd \qquad (5)$$

$$h2 = B * 1\ mm/(5.0 - B) \qquad (6)$$

The results from this analysis show that the RSMS has the capability to measure the radiation emitted from a spot on the burning surface and can meet the DARTFire experiment requirement. The longest diameter of the spot is 4.8394 mm at the wavelength of 8 μm. For the wavelength of 14 μm, the spot diameter is 4.766 mm. In both cases, radiation emitted from the central part of the spot is 100 percent received by the 2- by 2-mm sensor area of the detector. The sizes of the central area of the spot are different: for 8 μm, the diameter of the central area is 3.5832 mm, for 14 μm it is 3.6834 mm.

System analysis.—

Relationship between the spot radius and the radiation percentage received by the RSMS: Based on the ray-tracing technique with application of Snell's law, simulation results are plotted in figure 5. This plot shows that the diameter of the spot, over which radiation is measured, varies with the radiation wavelength, and with the radiation percentage received by the sensor area of the detector. For the radiation percentage above 50 percent, the spot radius becomes shorter for shorter wavelength. For the radiation percentage below 50 percent, the spot radius becomes longer for shorter wavelength. When the spot size exceed 5-mm diameter, the radiation from the burning surface does not reach the sensor area of the detector.

The radiation detected by the RSMS from the spot: Figure 6 shows the percentage of radiation received by the RSMS from the spot on the burning surface at 14 μm. This figure indicates that 100 percent of the radiation from the center area A is received by the RSMS. The amount of radiation received from area B decreases in a near-linear fashion from 100 percent at the inner diameter to 0 percent at the outer diameter. For wavelength shorter than 14 μm, the diameter of area B increases slightly to encompass area C at a wavelength of 8 μm.

System design is based on the lens parameters, and system analysis is based on the ray-tracing technique. They both have the same result: the maximum diameter of the spot is close to 5 mm, and 100 percent of the radiation emitting from the center part of the spot can be detected by the detector. The RSMS meets the requirement.

Calibration

Repeatability test.—Table V gives three sets of data collected with the RSMS system facing the exit aperture of the blackbody source. The diameter of the exit aperture is 2.54 cm. Figure 7 shows a schematic of the test setup. An amplifier with a gain of 200 was connected between the RSMS system and the voltmeter to increase the output for estimating the error in the measurement. During data collection, only the temperature of the blackbody source was varied. For each run, the temperature was tuned from 50 to 1000 °C in 50 °C increments.

In table V, the fifth column lists the average values (mean or expected value) at given temperature, the sixth column lists the maximum deviation of the mean, and the last column, the repeatability error percentage. According to the analysis, this error varies with the temperature range over which the measurements are performed. The repeatability error is 9.57 percent for the temperature range of 50 to 100 °C, and the maximum error occurs at 50 °C. In the temperature range of 100 to 1000 °C, the maximum error is 0.62 percent, occurring at 350 °C. It would be 0.35 percent, if the temperature is above 500 °C, the maximum error is 0.35 percent. The total system repeatability error is the sum of the blackbody error and the repeatability error.

Curve fitting.—To perform the curve-fitting process, a set of data including the RSMS output and blackbody temperature was collected in table VI. The connections among the RSMS system, the blackbody source, and the voltmeter were similar to that in the repeatability test, except that the output of the RSMS system was directly connected to the input of the voltmeter, as shown in figure 8.

Through the curve-fitting process, a power equation was selected to fit the calibration data:

$$T_{BB} = b * X^{a} \tag{7}$$

where

a 0.65925

b 6.49086

X output voltage of RSMS, unit in μV

T_{BB} is the temperature of the blackbody source

The output voltage of RSMS includes some measurement error discussed in repeatability test. Therefore, the total error results from the curve fitting is

$$\text{Error percentage} = \{b * [X * (1 + \text{Repeatability error percentage}/100.0)]^{a} - T_{BB}\} * 100/T_{BB} \tag{8}$$

In equation (8), the values of a and b are the same as that in equation (7). T_{BB} is the temperature listed in table VI column 1, and X is the measured data listed in column 2 of the same table. The repeatability error percentages are listed in table V column 7. By substituting those data in equation (8), we have the curve fit error percentages, including the repeatability error, listed in table VI column 3.

The plots of the power equation and the calibration data versus the blackbody temperature (the first two columns in table VI), are shown in figure 9. The calibration data set curve shows the relation between RSMS output and the blackbody temperature. If this curve is used to determine the blackbody temperature from RSMS output, the only error involved will be the repeatability error.

According to the relative location of the radiometric measurement in figure 2, there is an angle θ between the axis of the RSMS and the normal line of the burning surface, and an amplifier with a gain of A between RSMS and the voltmeter. If the burning surface is a blackbody, the temperature of the spot on the burning surface may be computed with equation (7), but the output of the RSMS, X, should be modified as follows.

$$X = [(V_s/A)/\cos\theta] \tag{9}$$

where

V_s is the voltage measured from the radiometric measuring system in µV

A is the amplification of the amplifier connected between the RSMS and the voltmeter

θ is the angle between the axis of the RSMS and the normal of the radiation surface

It should be noted that all the dimensional errors need to be considered in the computation.

The fourth column in table VI, lists the radiation, from 8 to 14 µm, emitted from the 5-mm diameter spot on the exit aperture of the blackbody source. Those figures in the fourth column are computed from the following equations (ref. 2).

$$P_{8\text{ to }14\ \mu m\text{ power}} = \pi * N * A \tag{10}$$

where $A = \pi * R^2$ is the area of the spot.

$$N = \sum_{\lambda = 8\ \mu m}^{14\ \mu m} \left\{ (2hc^2/\lambda^5) * [\exp(hc/\lambda k T) - 1]^{-1} \right\}$$

where

h is Planck's constant

c is the velocity of the light, λ is the wavelength of the radiation

k is the Boltzmann's constant

T is the absolute temperature

R is the radius of the spot

The fourth column combined with the second column in table VI generates a curve as shown in figure 10, which shows the radiation emitted from the 5-mm diameter spot versus the output from RSMS. Through curve-fitting process, the same set of data generates a straight line equation which can be used to compute the same radiation emitted from the spot. In the experiment, the amount of the radiation emitted from the 5-mm diameter spot may be found from the curve or from the straight line equation when the RSMS output is known and the burning material is a blackbody.

The curve-fitting error including the repeatability error, above 200 °C, is 1.6 percent, the maximum error occurs at 500 °C of the blackbody temperature. The equations are as follows.

$$\text{Radiation}_{(spot)} = a_{(E)} * X_{(\mu v)} + b_{(E)} \tag{11}$$

where

$a_{(E)}$ 0.0935091

$b_{(E)}$ 2.07143

X RSMS output

$$\text{Error percentage} = \{a_{(E)} * X * (1 + \text{Repeatability error percentage}/100) + b_{(E)} - \text{Radiation}_{(spot)}\} * 100.0/\text{Radiation}_{(spot)} \quad (12)$$

CONCLUSION

This Radiometry Spot Measurement System (RSMS) is designed for the Diffusive And Radiative Transport in Fires (DARTFire) experiment. The RSMS has the ability to measure the radiation and the temperature of the 5-mm diameter spot on a blackbody burning sample. The simulation results verify RSMS performance.

REFERENCES

1. Smith, W.J.: Modern Optical Engineering: The Design of Optical Systems. 2nd ed., McGraw-Hill, Inc., New York, 1990.

2. Wyatt, C.L.: Radiometric Calibration: Theory and Methods. Academic Press, New York, 1978.

TABLE I.—SPECIFICTIONS OF THE LENSES*

	Objective lens, cm	Imaging lens, cm
Curvature radius, R	13.8532	6.7310
Center thickness, t	.3048	.3048
Edge thickness, te	.2540	.2540

TABLE II.—REFRACTION INDEX OF THE KRS–5*

Wavelength, μm	Refraction index
8	2.374
10	2.370
12	2.367
14	2.361

*Information provided by Infrared Optical Products, Inc.

TABLE III.—LENS PARAMETERS VARY WITH THE WAVELENGTH

	Wavelength, cm		Equation number
	8 μm	14 μm	
Objective lens focal length, fa	10.0824	10.1787	(1)
Imaging lens focal length, fb	4.8988	4.9456	(1)
System focal length, fab	3.4780	3.5094	(2)
System front focus dist., ffd	2.9242	2.9559	(3)
System back focus dist., B	3.2089	3.2405	(4)

TABLE IV.—THE RADII VARY WITH THE WAVELENGTH

		Wavelength, mm	
		8 μm	14 μ
Radius	h1	2.4197	2.3830
Radius	h2	1.7916	1.8417

TABLE V.—REPEATABILITY TEST DATA

Temperature of BB, C°	Data set I, mv	Data set II, mv	Data set III, mv	Average value, mv	Maximum deviation of the mean, mv	Repeat error, percent
50	4.38	5.13	5.02	4.84	0.46	9.57
100	13.19	13.23	13.33	13.25	0.08	0.60
150	24.25	24.24	24.15	24.21	0.06	0.26
200	37.67	37.35	37.35	37.46	0.21	0.57
250	53.03	52.58	52.84	52.82	0.24	0.45
300	69.97	69.50	69.54	69.67	0.30	0.43
350	88.60	87.89	87.67	88.05	0.55	0.62
400	108.34	107.84	107.48	107.89	0.45	0.42
450	128.62	128.67	128.36	128.55	0.19	0.15
500	150.70	149.72	150.10	150.17	0.53	0.35
550	172.73	172.54	172.86	172.71	0.17	0.10
600	196.14	194.76	195.86	195.59	0.83	0.42
650	220.08	219.10	219.70	219.63	0.53	0.24
700	244.50	244.04	243.81	244.12	0.83	0.16
750	269.16	269.88	268.81	269.28	0.60	0.22
800	295.71	294.94	295.39	295.35	0.41	0.14
850	322.66	320.99	320.67	321.44	1.22	0.38
900	348.82	348.14	347.13	348.03	0.90	0.26
950	374.61	373.77	373.89	374.09	0.52	0.14
1000	400.17	399.57	399.08	399.61	0.56	0.14

TABLE VI.—CALIBRATION DATA SET

Temperature of BB, mW	Data set, C°	Curve-fit, μV	Radiation, from spot, percent
50.0	20.5	0.99	4.78379
100.0	62.9	−0.05	8.57518
150.0	118.1	0.71	13.5343
200.0	185.2	1.82	19.5594
250.0	263.8	2.77	26.5268
300.0	346.1	2.42	34.3122
350.0	436.4	2.42	42.8020
400.0	536.0	2.48	51.8961
450.0	639.1	2.11	61.5086
500.0	753.0	2.53	71.5668
550.0	864.4	1.92	82.0093
600.0	976.7	1.48	92.7845
650.0	1088.1	0.46	103.8490
700.0	1207.3	−0.15	115.1650
750.0	1329.1	−0.67	126.7030
800.0	1456.7	−1.13	138.4360
850.0	1588.6	−1.32	150.3410
900.0	1713.7	−2.10	162.3990
950.0	1841.7	−2.82	174.5930
1000.0	1970.1	−3.49	186.9080

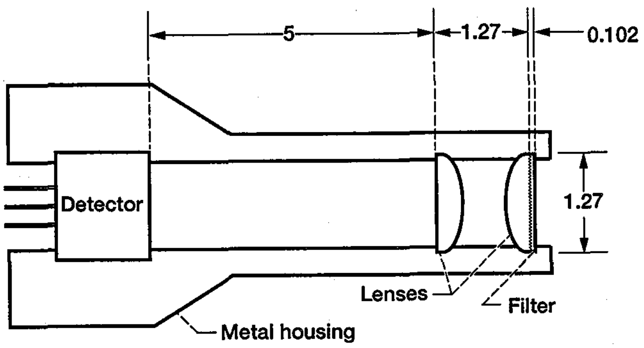

Figure 1.—RSMS structure. Dimensions are in cm.

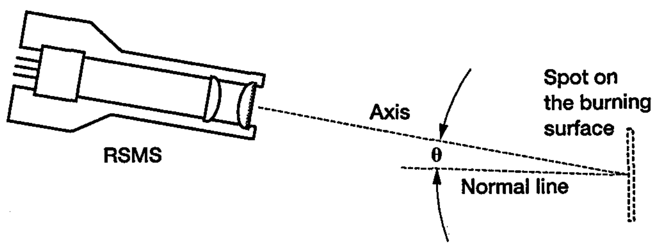

Figure 2.—Relative locations of radiometric measurement.

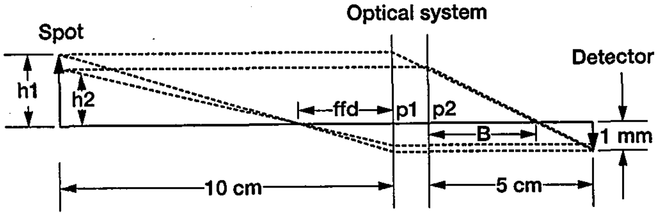

Figure 3.—Image position for RSMS.

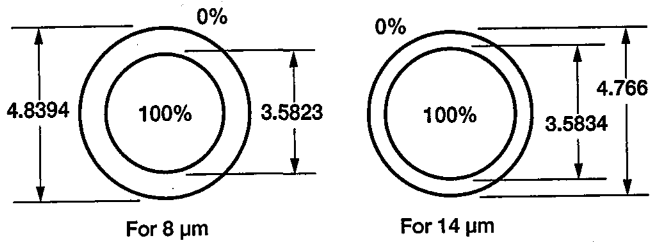

Figure 4.—Spot diagram. Dimensions are in mm.

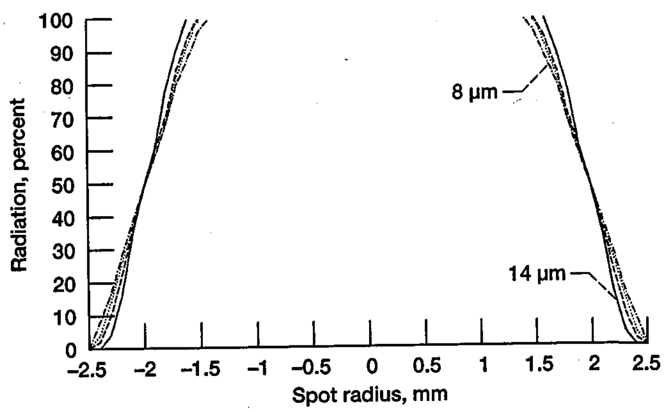

Figure 5.—Radiation percentage vs. spot radius.

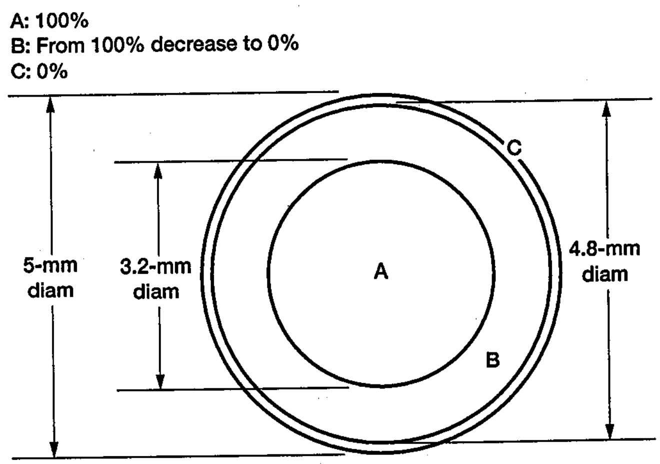

Figure 6.—Radiation detected by RSMS from spot at 14 μm.

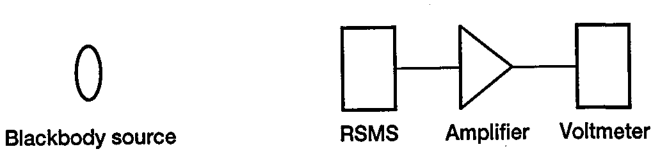

Figure 7.—Schematic of repeatability test.

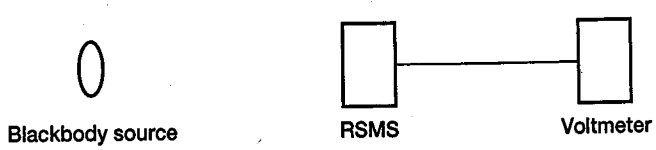

Figure 8.—Schematic of calibration configuration.

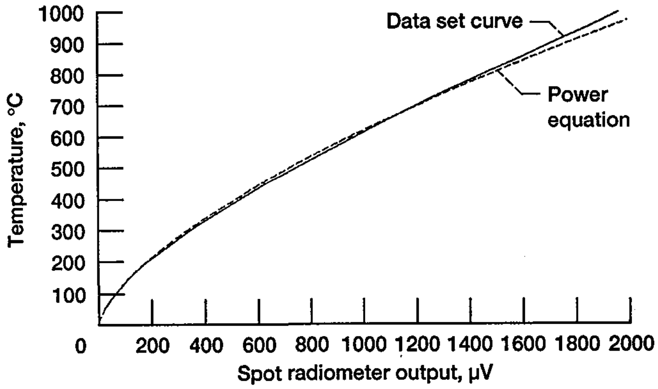

Figure 9.—Power equation and calibration data set curves.

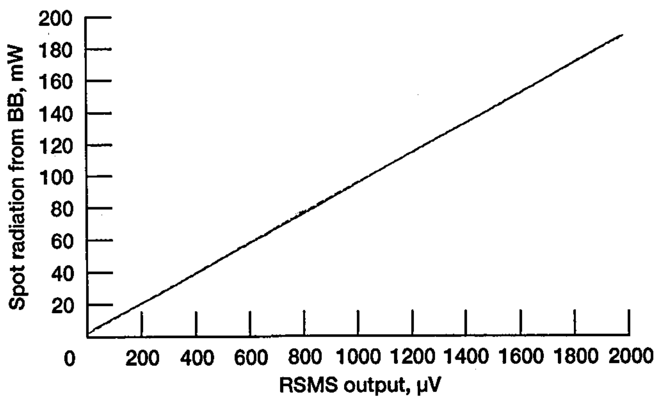

Figure 10.—Radiation from spot vs. output from RSMS.

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13. ABSTRACT ***(Maximum 200 words)***

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